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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This document reports on work toward a very low rate phonetic vocoder and a multirate speech compression system. The phonetic vocoder consists of a phonetic recognizer based on a trained diphone network, and a natural phonetic synthesizer which also uses diphone templates as a model for speech. This quarter, the basic data base of transcribed diphones for the phonetic synthesizer was completed. There are currently 2652 diphones.

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The initial versions of the diphone network compiler and network matcher programs for phonetic recognition were also implemented. On the multirate speech compression system, further modifications and improvements to the basic baseband ATC algorithm were tried.

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1. SUMMARY

In this Quarterly Progress Report, we present our work performed during the period September 8, 1979 to December 7, 1979.

1.1 Introduction

Our research during this past quarter was divided among the areas of natural phonetic synthesis, phonetic recognition, and a multirate speech compression system. The phonetic recognition and synthesis programs will operate together as a very low rate phonetic vocoder. Each of the following subsections (1.2, 1.3, 1.4) refers to one section of the remainder of the QPR (Sections 2, 3, and 4).

1.2 Synthesis

During this quarter we achieved a major milestone in the phonetic synthesis project by completing the transcription of the initial set of diphone utterances. This means that we are now capable of synthesizing any arbitrary English sentence. There will, however, be some additional labelling effort associated with the exhaustive testing of the diphone data base.

We have also added new testing modules to the synthesis program and have been testing diphones both in isolation and in complete sentences. Only relatively minor changes and corrections have been made this quarter to the synthesis program itself. We feel that the program design is now stable.

The labelled data base is described in Section 2.1. The progress made on testing is discussed in Section 2.2, and the few program changes are listed in Section 2.3.

1.3 Phonetic Recognition

Preliminary versions of the diphone network compiler and diphone matcher were implemented during this past quarter. The design of the diphone recognition system also underwent considerable change. These changes, and in particular, the scoring philosophy embodied in the programs, are discussed in Section 3.1. The status of the program implementation is reported in Section 3.2. In Section 3.3 we outline the planned tasks in recognition for the remaining six months of the current contract year. Though there will be some amount of research into better program design and scoring metrics, the bulk of the remaining effort will be expended in training the recognition system on large amounts of speech to improve its performance.

1.4 Multirate Coding

At the beginning of this quarter, the quality of transform-coded speech was somewhat rough. For the full-band ATC system operating at 16 kb/s, the roughness is due to quantization noise, while for the multirate system operating at 9.6 kb/s or below the roughness is mainly due to the regeneration of missing high-frequency components. In this report, we discuss the full-band 16 kb/s case. We were able to achieve a substantial improvement in coder performance by an improved bit-allocation scheme and by optimum quantization. These matters are discussed in Section 4.

As for the multirate case, its output speech quality is mostly governed by the HFR (high-frequency regeneration) technique used. For that reason, we are currently working on improved HFR methods. We defer any discussions on the multirate system until the next quarterly progress report.

2. SYNTHESIS

During this quarter we achieved a major milestone in the phonetic synthesis project by completing the transcription of the initial set of diphone utterances. This means that we are now capable of synthesizing any arbitrary English sentence. There will, however, be some additional labelling effort associated with the exhaustive testing of the diphone data base.

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The labelled data base is described in Section 2.1. The progress made on testing is discussed in Section 2.2, and the few program changes are listed in Section 2.3.

2.1 Diphone Data Base

As of the end of this quarter, we have completed the initial transcription (labelling) of the diphone data base. There are currently 2652 diphones in the data base. The ongoing testing (Section 2.2) presently indicates that about 10% of these diphone labels will require modification. As we test the synthesizer with complete sentences, we may find that we need a few additional diphones. These will primarily be diphones in a particular phonetic context that could not be taken from the unconstrained context.

In Appendix A we list by category all the different diphones currently in the data base. Appendix B contains an alphabetized list of the 2652 diphones.

2.2 Diphone Testing

Now that the basic inventory of diphones is complete, we can synthesize any arbitrary English phoneme sequence. All that remains in this phase of the synthesis project is to test all the diphones exhaustively using the automatic test sequence generators, and also to synthesize a number of full sentences to verify that the speech sounds natural.

Last quarter we described a feature in the phonetic synthesizer that automatically generated CVC sequences to facilitate testing of the CV and VC diphones. This past quarter, we added a sequence generator to test CC diphones. This new sequence generator synthesizes nonsense strings of the form:

$$- C_1 \; V \; C_2 \; C_1 \; V \; C_2 \; -.$$

To illustrate, consider the testing of the diphone [N S]. The testing program would synthesize the following nonsense sequence:

- S EH N S EH N -

The [N S] diphone is used in the middle of this sequence. We will shortly be implementing another option that will generate sequences to test VV diphones in a similar manner.

At present, we have completed testing of approximately 10% of the diphones. The procedure began quite slowly, because we encountered several diphones that did not sound natural. However, as we corrected these, we also were able to generalize the changes to many other related diphones, so that the testing is now progressing more rapidly. Most of the remaining errors are expected to be due to accidental misplacement of phoneme boundaries in the short nonsense utterances from which the diphones were extracted.

In addition to testing the diphones exhaustively in isolation, we shall be testing them by synthesizing a large number of full sentences. Since completing the diphone inventory we have synthesized seven complete sentences. These tests pointed out a small number of labeling and program errors which were then corrected. The quality of these sentences is markedly improved over that which we had obtained previously. We attribute this improvement to the small but significant program changes noted below, and the fact that we now have all of the diphones we need to synthesize unconstrained material.

2.3 Synthesis Program Changes

Changes to the synthesis program this quarter have consisted of the addition of the automated testing modules, and the correction of some program bugs in the diphone concatenation subroutines. The automated testing modules have been described above, as well as in previous reports. The few program bugs which we have corrected appear to be the last of the logical errors of this type. However, as we test large amounts of data we may arrive at modifications to the reported procedures that result in more natural sounding synthesis.

3. PHONETIC RECOGNITION

A good deal of the time spent last quarter on diphone template recognition was used to design the system. We continue to present this design in Section 3.1 by describing the scoring philosophy in considerable detail. During this past quarter, we implemented the bulk of the programs necessary for the basic design as presented. This implementation work is described in Section 3.2. The kind of work that we anticipate during the remainder of the project is spelled out in Section 3.3.

3.1 Scoring Philosophy

The scoring philosophy plays a particularly important part in the operation of our diphone template recognition system. Simply stated, the goal of the recognition system is to pick the most probable phoneme sequence given the sequence of input speech spectra. The scoring philosophy determines how such probabilities are to be accurately calculated.

In this section we will systematically derive our scoring philosophy and indicate how far the current implementation goes towards its realization. In this derivation the scoring philosophy is spelled out in an incremental sense. In order to do this we start with a simple expression, which represents the probability of a particular path given the input, and systematically decompose it via a sequence of equivalence transformations and approximations into the product of many simple expressions. Since each of these simple expressions can be calculated independently, a scoring adjustment can be made (to previous path scores) for each additional input spectrum. As we proceed, many of the more salient approximations will be pointed out and justified.

At present we are modeling the input speech spectra by the LPC coefficients plus the associated gain.

Let I_i, $i = 1,N$, be the sequence of spectral frames modeling the input, and let P_k^j, $k = 1,M^j$, be the jth path of spectral frames through the network, where the number of input frames is at least as great as the number of frames in path j ($N \geq M^j$) for every j. Also, let Prob^j be the probability of the jth path given the input:

$$\mathrm{Prob}^j = \mathrm{Prob}(P_i^j,\ i=1,M^j \mid I_k,\ k=1,N)$$

Specifying any unique path through the network indirectly determines a unique phoneme sequence (since the phonemes are identified by labelled nodes along the path). Currently, since only a single path directly connects any two phonemes in the network, the converse is also true, i.e., specifying a unique diphone sequence determines a unique network path. This second part will not, in general, be true when additional paths are added.

Noting that our recognition goal is to determine the most probable path, we now consider how to score a single path. For notational convenience we shall remove the superscript used to identify which of the j paths through the network is being scored. We begin the decomposition of this probability with the following equivalence relationship, using Bayes´ Rule:

$$\mathrm{Prob}(P_1P_2.\,.\,P_M|I_1I_2.\,.\,I_N) = \tag{1}$$
$$\mathrm{Prob}(P_1P_2.\,.\,P_M)*\mathrm{Prob}(I_1I_2.\,.\,I_N|P_1P_2.\,.\,P_M)/\mathrm{Prob}(I_1I_2.\,.\,I_N)$$

The third term of this expression, $\mathrm{Prob}(I_1I_2.\,.\,I_N)$, is independent of the particular path through the network and therefore does not need to be evaluated in order to correctly find the most probable path. Note, however, that for incomplete path scores to be meaningfully compared, each path should span the same input. Having made this observation, we will not deal with the evaluation of $\mathrm{Prob}(I_1I_2.\,.\,I_N)$ here.

The first term, $\mathrm{Prob}(P_1P_2.\,.\,P_M)$, is the a priori probability of the particular path being considered. Since the path actually is composed of a sequence of diphone models and each diphone model is itself defined by a sequence of spectral frames, this probability is exactly the same as the a priori probability of the particular diphone sequence. The approximation made in the current implementation is to assume that the presence of each diphone in the sequence is independent of the other diphones, as long as the implied context is satisfied. For example, diphones whose right phoneme is X can only be followed by diphones whose left phoneme is X.

The most important (and interesting) part of the path score will result from the second term, $Prob(I_1 I_2 . . I_N | P_1 P_2 . . P_M)$. This term tells how probable it is that the observed input would have been produced if it was known to have been produced as a result of "speaking" along the specified path.

Remember that $N \geq M$ since each of the spectral frames in the path must have at least one corresponding spectral frame in the input. Certain precautions have been taken to insure that this is a reasonable constraint. For example, a variable frame rate algorithm is used by the network compiler to insure that each diphone model consists of a sequence of substantially different spectral frames.

The next step in the decomposition of (1) consists of relating the evaluation of the important second term to alignment considerations. An alignment is the correspondence between the frames in the input and the frames in the path being scored.

$$\mathrm{Prob}(I_1I_2. . I_N|P_1P_2. . P_M) = \sum_{i=1}^{Num} \mathrm{Prob}(\mathrm{Alignment}_i) * \mathrm{Prob}(I_1I_2. . I_N|P_1P_2. . P_M\ \mathrm{Alignment}_i) \qquad (2)$$

where Num is the number of different possible alignments.

What this means is that an exact evaluation of (2) requires knowledge of all possible ways in which to align the given path with the observed input. At this point we detail a few of the assumptions which permit a further evaluation of this probability. The first assumption is that the time ordering of spectral frames of both diphone models and input speech is significant. A second assumption is that in defining any particular alignment the only relevant thing that can be said is how many input frames are to be associated with each of the spectral frames in the path. Since we have already asserted that each of the spectral frames in the path must have at least one corresponding frame in the input, the alignment can be completely defined by a sequence of M durations, $D_1D_2. . D_M$, one duration for each of the spectral frames in the path.

Since each alignment will be characterized by a different set of durations, we only need to consider the evaluation of the probability for an arbitrary alignment. Note that the number of input frames is equal to the sum of these durations, $(N = \sum_{k=1}^{M} D_k)$, since each spectral frame in the input is aligned with one (and only one) of the spectral frames in the path. Let us consider the evaluation of an arbitrary alignment.

Prob(Alignment) = Prob($D_1D_2. . D_M$) This is the joint probability that P_1 corresponds to D_1 frames of input, P_2 corresponds to D_2 frames of input, ... , and that P_M corresponds to D_M frames of input. Note that this alignment probability is independent of any particular sequence of input spectral frames. We approximate $P(D_1D_2. . D_M)$ as $P(D_1)*P(D_2)*.*.*P(D_M)$. This is equivalent to assuming that the alignment of each frame in the path is independent of the alignment of every other frame in the path. Having selected Alignment($D_1D_2. . D_M$), and remembering that the alignment of each path frame has been assumed to be independent of all other path frames, we note that:

$$\begin{aligned} &\mathrm{Prob}(I_1I_2. . I_N|P_1P_2. . P_M\ \mathrm{Alignment}(D_1D_2. . D_M)) = \qquad (3)\\ &\quad \mathrm{Prob}(I_1. . I_{D_1}|P_1. .)*\\ &\quad \mathrm{Prob}(I_{D_1+1}. . I_{D_1+D_2}|. P_2. . I_1. I_{D_1})*\\ &\quad .\\ &\quad .\\ &\quad \mathrm{Prob}(I_{D_1+D_2+...+D_{M-1}+1}. . I_{D_1+D_2+...+D_{M-1}+D_M}|. . P_MI_1. . I_{D_{M-1}}) \end{aligned}$$

In writing (3) the correspondence between each path frame and its corresponding input frame(s) is implied by notation. We now assume that the probability of every input frame depends only on the particular path frame to which it is aligned. This results in the following simplification:

$$\begin{aligned} &Prob(I_1 I_2 . . I_N | P_1 P_2 . . P_M \ Alignment(D_1 D_2 . . D_M)) = \qquad (4) \\ &\quad Prob(I_1 . . I_{D_1} | P_1) * \\ &\quad Prob(I_{D_1+1} . . I_{D_1+D_2} | P_2) * \\ &\quad . \\ &\quad . \\ &\quad Prob(I_{D_1+D_2+...+D_{M-1}+1} . . I_{D_1+D_2+...+D_{M-1}+D_M} | P_M) \end{aligned}$$

We now make the additional assumption that the probability of any particular input frame, given a corresponding path frame, is independent of other input frames. The right-hand terms in (4) can then be further expanded as:

$$\begin{aligned} &Prob(I_1 I_2 . . I_N | P_1 P_2 . . P_M \ Alignment(D_1 D_2 . . D_M)) = \qquad (5) \\ &\quad Prob(I_1 | P_1) * ... * Prob(I_{D_1} | P_1) * \\ &\quad Prob(I_{D_1+1} | P_2) * ... * Prob(I_{D_1+D_2} | P_2) * \\ &\quad . \\ &\quad . \\ &\quad Prob(I_{D_1+D_2+...+D_{M-1}+1} | P_M) * ... * Prob(I_{D_1+D_2+...+D_{M-1}+D_M} | P_M) \end{aligned}$$

Notice that the last referenced input frame, $I_{D_1+D_2+...+D_{M-1}+D_M}$, is frame I_N. Although the scoring philosophy and a few assumptions and approximations have permitted us to proceed this far, we can see that several important issues still remain to be resolved before a scoring algorithm can be implemented.

The first of these issues involves the evaluation of the probabilities indicated in (5). All of the probabilities are of the same basic form: Prob(I|P). The probability of a particular input spectral frame must be calculated given the particular path spectral frame of which it is an instance. Currently the weighted Euclidean distance between the two spectral frames is used as a scoring metric in lieu of the log probability. This is equivalent to assuming that every path frame has a Gaussian distribution of input spectra. The mean of each such distribution is the path spectral sequence itself. A generalized implementation of the scoring philosophy is discussed in Section 3.2.2.

A second implementation issue concerns the alignment probabilities. Notice that the scoring philosophy (as expanded) only indicated how a known duration probability would affect the score of an entire path. A decision has to be made as to what (if any) score effect should be applied during the matching process, before the final duration is known. Since what is known is that the duration of the current path spectral frame is (for example) <u>at least</u> j frames long, the score is modified so as to include the <u>expected</u> value of the duration probability.

$$\text{Expected value} = \sum_{i=j}^{Max} Prob(D(i))*Prob(D(i))$$

where Prob(D(i)) is the probability that the duration of this path frame is i input frames long.

3.2 Current Status - Implementation

The software work involved in the diphone template recognition project consists of two major components. First, there is a diphone network compiler which takes a text file of diphone descriptions as input and produces diphone network which can be used by the matcher program during recognition. The second component is the matcher, which uses this compiled network and produces the best scoring phoneme sequence given a sequence of input spectral frames.

3.2.1 Network Compiler

During this quarter an initial version of a network compiler was implemented. It takes diphone definitions in the same format as COMPOZ (the diphone compiler used by the synthesis program) does with one minor difference. Diphones <u>without</u> context must appear before those <u>with</u> context. This permitted a considerably simpler algorithm than the one which would have been necessary had this constraint not been imposed. Eventually, however, since we would like the capability to do arbitrary incremental additions to the network, the compiler will probably be extended. We have used this network compiler to generate a complete network of all the diphones currently available (approximately 2600).

3.2.2 Matcher

A matcher that satisfies the basic considerations in the design set forth in the last QPR [1] has been implemented and is currently running. These considerations include: 1) a sound scoring strategy, 2) continuous operation, 3) alignment availability for training, and 4) efficiency. Since the matcher appears to be operating as it should (no apparent bugs), our attention is turning to a generalization of the currently implemented spectral scoring procedure.

The most general scoring procedure would require a nonparametric model of the probability density distribution. For example, if we use samples of input frames known to have been aligned with a particular path spectral frame, such a probability can be estimated. (It is this procedure which was alluded to earlier when we indicated that the memory space on the current computer was affecting our current implementation.) Of course the mere collection of a sufficient number of instances of this path spectral frame would in itself be a significant data processing problem. A much simpler procedure would be to assume that a single parametric model can accurately represent the probability distribution of each path spectral frame if the collected instances are used to determine the parameter values. A still simpler procedure would be to assume that the uniform parametric model is Gaussian. The parameters in this case consist of the means and covariance matrix. To minimize both storage requirements and computation time, the implemented scoring algorithm adds the logarithm of the probabilities instead of multiplying the probabilities. The evaluation of the probability then reduces primarily to the determination of the Euclidean distance between the input and path spectral frames.

3.3 Future Work

We anticipate that the following list of activities will require most of our time during the remainder of this project:

1) Debugging, testing and evaluation of the current system
2) Forced alignment with time boundaries specified
3) Completion of statistics code
4) Generalization of spectral scoring
5) Training

Since we have enough code implemented to permit the operation of the entire diphone template recognition system, we feel that it will be advantageous to get the best possible performance before resorting to all of the statistically based techniques. The reason for this belief is that many word matchers and word spotters have been based entirely on a spectral matching technique (and dynamic programming) and have gotten relatively good performance for up to a few hundred words. While we don't expect quite the same level of performance (we are using much shorter segments and some contextual variation) we do expect that a reasonable level of performance should be possible. Knowing this level will also be handy as a reference during the testing training program. In achieving this level of performance we will no doubt uncover some bugs, which might be overlooked if we were to go immediately to a more complex system.

Currently, forced alignment between input speech and the diphone network can only be specified as an ordered sequence of diphones. Although this may be sufficient for most of the cases where forced alignment is necessary, it will probably not be sufficient for every situation. It may therefore be necessary to include the capability to specify the frame numbers in the input as an additional alignment constraint in these special cases. If this proves necessary, not much programming will be required since it is a straightforward addition to the current forced alignment code.

Code to update the duration statistics, given a particular path frame and a new sample duration, has already been written.

What remains to be coded is an interface to this code which permits a user (who knows what the "correct" segmentation and labeling should be) to identify which portions (or perhaps all) of the algorithmically aligned input should be used for statistically updating duration distributions. It may be necessary for the user to exclude certain portions of the alignment because a really suitable path does not currently exist in the network. Permitting the user to identify some portion of the input which was poorly matched and include that portion in the network as a new diphone path (or portion of a diphone path) will probably be necessary as well.

Some work on the generalization of spectral scoring will undoubtedly be done. How far the spectral scoring metrics can be pushed depends, to a large degree, on the amount of speech which we can reasonable expect to train the system on. Another possible limitation has to do with the amount of memory necessary to represent the (potentially) more accurate metrics. It is very easy to conceive of metrics, whose implementation would require substantially more memory than that which is (currently) addressable on a PDP-10. Unless an extension is made to its address space (in a way which permits such large amounts of memory to be easily accessed) these very general scoring techniques will not be implemented.

Once the program bugs have been eliminated, a substantial part of the remainder of the project will consist of training the system on input speech. Although it is much too early now to estimate what level of performance will be possible, we hope to be able to make such an estimate later on in the project. We propose also to present a record of the improvement in performance as a function of time (or sentences processed etc.). This will enable us to determine more accurately just how much training will be necessary to get a certain level of performance and what level of performance we might expect to achieve.

4. MULTIRATE CODING

4.1 Introduction

During this quarter we have concentrated our efforts at improving the quality of transform-coded speech. We have worked mainly on the full-band 16 kb/s ATC system, with the knowledge that our improvements will be applicable to both the 9.6 kb/s baseband coder and to the general multirate system. Below, we discuss the major cause of quality degradation in the ATC system: quantization noise. We then discuss the two areas in which we were able to achieve a substantial improvement in coder performance: bit-allocation and optimum quantization. For simplicity, we shall restrict our discussions to ATC without noise shaping. All our results are applicable to the case with noise shaping as well.

4.2 Quantization Noise

In this section we first describe briefly the quantization of the DCT. We then discuss the effect of quantization noise on quality. In our implementation of ATC, we are quantizing the DCT coefficients of the linear prediction residual with a frequency-dependent step-size D_i given by

$$D_i = D_0 |A_i| \qquad 1 \le i \le 128 \qquad (6)$$

where D_0 is an experimentally derived constant to be discussed below, and $|A_i|$ is $|A(w)|$, the magnitude of the DFT of the linear prediction inverse filter A(z). Initially, we used uniform n-bit quantizers with step-size D_i, for $0 \leq n \leq 12$. (In practice, n never exceeds 10.) Thus, the quantization of the DCT components can be represented by the following two steps:

$$t_i = \lfloor x_i/D_i \rceil \tag{7}$$

and

$$\hat{x}_i = t_i D_i \tag{8}$$

where t_i is a temporary variable, $\lfloor \cdot \rceil$ denotes taking the nearest integer value, x_i is the ith DCT component of the residual, and $\hat{x}_i$ is its quantized value. Note that the integer variable t_i indicates which quantization level is used; it is encoded into a binary code and transmitted across the channel. Substituting (6) into (7), we have

$$t_i = \lfloor (x_i/|A_i|)/D_0 \rceil \tag{9}$$

In (9), the term in parenthesis has the same energy and the same spectral shape as the DCT of the speech signal itself. Thus, to a good approximation, our method is equivalent to quantizing the DCT coefficients of the speech signal with a fixed step-size D_0. The process of quantizing the DCT of speech has been described in the literature and is given the name of ATC. It should maximize the output signal-to-quantization-noise ratio (SNR) for a given number of bits. For the full-band 16 kb/s case, the quality of the output speech we obtained initially was somewhat rough, due to excessive granular noise and/or clipping.

The problem arises when we make a choice of step-size D_0 for the uniform quantizers. For reasonably small D_0, the granular noise is negligible, but the clipping errors are quite frequent and large, causing an appreciable decrease in SNR and a severe degradation in the quality of the coded speech. As the step-size D_0 is increased, the clipping problem is alleviated, the SNR increases, but the granular noise becomes more audible (in the form of roughness). For still larger D_0, the granular noise becomes excessive and the SNR drops again. During the previous quarter, we were able to reach a suitable compromise value for D_0, but some roughness was still perceivable in the coded speech. During this quarter, in an attempt to improve the quality of the coded speech, we reexamined the bit-allocation process and found that the spectral model of the signal must not be quantized with a 6-dB step-size. The modified bit-allocation scheme is discussed in the following section.

4.3 Bit-Allocation

Recall from the previous QPR that the number of bits to be used at each frequency is given by

$$b_i = b_0 + \log_2(1/|H_i|) \qquad 1 \leq i \leq 128 \tag{10}$$

where $1/|H_i|$ is $1/|H(w)|$, the magnitude of the DFT of the spectral model of the speech signal, and b_0 is the average number of bits per sample for a given bit-rate. The spectral model of speech was discussed in the previous QPR; briefly, it consists of two components: a smooth (LPC) spectral envelope, and a model for the harmonic structure of the spectrum (pitch). The fractional numbers b_i obtained in (10) are quantized to become integers $\hat{b}_i$, subject to the following constraints: (i) no negative bit-assignment is allowed, and (ii) the sum of integer $\hat{b}_i$ must equal B, the number of available bits per frame. This integerization process is given by

$$\hat{b}_i = \max\{0, \lfloor b_i+\beta \rceil\} \tag{11}$$

such that

$$\sum_{i=1}^{128} \hat{b}_i = B \tag{12}$$

The adjustment constant β in (11) is varied iteratively until (12) is satisfied. The process depicted in (11) is in fact quantization of the spectral model of the speech signal on a logarithmic scale. To see that, we rewrite (10) as

$$b_i = b_0 + \frac{1}{2}\log_2(1/|H_i|^2)$$

or,

$$b_i = b_0 + \frac{10}{6.02}\log_{10}(1/|H_i|^2) \tag{13}$$

In (13), we recognize the familiar term $10\log_{10}(1/|H_i|^2)$, which is the spectral model of the speech signal expressed in decibels.

Thus, from (13) and (11), it becomes clear that, to obtain the allocated bits $\hat{b}_i$, we are quantizing the spectral model with a 6.02 dB step-size (and an offset equal to $b_0+\beta$). Note that this uniform quantization process begins by a division as shown in (13), while the rounding-off to integers is shown in (11). The 6-dB step-size interpretation of the bit-allocation scheme has been mentioned in the literature. We shall now denote this step-size by S and (13) can be rewritten as

$$b_i = b_0 + 10 \, [\log_{10}(1/|H_i|^2)]/S \qquad (14)$$

To alleviate the clipping/granular noise tradeoff problem discussed in Section 4.2, we decided to change the 6-dB step-size shown in (13). In particular, one can show that for a step-size S smaller than 6 dB, clipping is less likely to occur in the n-bit quantizers, for the same quantization step-size D_0. Thus, one can choose a small value of D_0 to minimize the amount of granular noise and, at the same time, adjust S such that the likelihood of clipping is also minimized. We hasten to say here that it is not always possible to find a suitable value of S for an arbitrarily small D_0. Also, for S<<6, a greater percentage of DCT components are quantized with zero bits. The 0-bit allocation is a problem in ATC; we shall discuss it in Section 4.5.

Informal listening over a set of 10 sentences, showed that the quality of the coded speech was much improved with a value of S of either 5 or 4 dB, relative to the case where S=6 dB. In fact, this improvement in quality was also accompanied by an average increase of 2 dB in the output segmental SNR.

4.4 Optimum Quantization

The second area where we were able to improve the SNR of the coded speech, is to replace the uniform quantizers by more optimal ones. To that end, we collected the statistics of the inputs to the n-bit quantizers. We found those inputs to have a Gaussian pdf (probability density function or histogram), as has been reported by others. Thus, to maximize the SNR, we decided to use Max's optimum non-uniform quantizers designed to minimize the mean-squared quantization error for Gaussian inputs [2]. For the same set of 10 sentences, the non-uniform optimum quantizers yielded an average increase of 1.2 dB in SNR over the case with uniform quantizers, for S=4 or 5 dB. However, perceptually, it was difficult to detect any change in the quality of the coded speech.

Finally, we have recently realized that the SNR of non-uniform quantizers optimized for a Gaussian pdf does not increase at the rate of 6 dB per bit. The values of the SNR of the n-bit Max quantizers for $0 \leq n \leq 5$ are shown in Table I.

n bits	0	1	2	3	4	5
SNR(n) dB	0.0	4.4	9.3	14.6	20.2	26.0
ΔSNR dB		4.4	4.9	5.3	5.6	5.8

Table I: Signal-to-noise ratio SNR(n) as a function of the number of bits for Max's optimum non-uniform quantizers. ΔSNR is the first forward difference.

From that table, it is clear that the increase in SNR approaches 6 dB for each 1-bit increase only for large n. In ATC, large values of n are seldom used: the quantizers most often used (95% of the time) are for $0 \le n \le 3$. Thus, Table I not only explains the improvement in performance for S=4 or 5 dB, but also indicates the use of a quantization scheme in (14) with unequal steps. We are now in the process of testing the newly modified bit-allocation scheme.

4.5 Conclusions

At present, the speech quality for the full-band coder at 16 kb/s is much improved relative to what it was at the beginning of this quarter. The quality of the coded speech is quite close to that of the original. Quantization noise is almost never perceived. However, one can perceive very low level clicks in the coded speech. We were able to determine that the cause of such clicks is related to the allocation of zero bits to certain DCT components. We performed an experiment where, following the usual bit-allocation with S=5, we allowed the use of a 1-bit quantizer for all samples that would normally be quantized with zero bits. Informal listening tests showed that all clicks disappeared from the coded speech. However, the above described solution causes an increase in bit-rate. We are now seeking solutions to this problem without increasing the bit rate. We are also in the process of testing the modified bit-allocation scheme which employs non-uniform quantization of the logarithm of the spectral model. And finally, we are testing the performance of the multirate coder, at 9.6 kb/s or below, with the improvements discussed in this report.

5. REFERENCES

[1] Berouti M., et. al., "Speech Compression and Synthesis," Quarterly Progress Report prepared for Advanced Research Projects Agency, BBN Report No. 4266, 8 June 1979 - 7 September 1979.

[2] Max, J. "Quantizing for Minimum Distortion", IRE trans. Inform. Theory, Vol. IT-6, pp. 7-12, March 1960.

APPENDIX A DIPHONE CATEGORIES

This Appendix contains a description of the eight major categories of diphones. Within each category is a definition of the set of all possible diphones of that type, and the number of total diphones in that category. In order for the reader to understand the notation that is used, we will examine the first category in some detail, and then note other notation in the remaining categories. The listing of the categories begins at the conclusion of these explanatory paragraphs.

The first category is entitled C_1V_1 (for Consonant-Vowel) diphones. The number 597 in parentheses indicates that there are 597 total diphones in this category. Below the category name are the sets of possible phonemes that can be substituted for C_1 and V_1. C_1 can be any one of the 25 consonants listed, and V_1 can be any one of the 24 vowels. To generate the possible C_1V_1 diphones, we begin by letting [P] be substituted for C_1, and let each of the 24 vowels be substituted in for V_1. This generates the diphones [P IY], [P IH], [P EY], [P EH], and so on up to [P AXR]. We then let C_1 be [T] and begin again, which produces [T IY], [T IH], and so on to [T AXR]. Below the definitions of C_1 and V_1 are three <u>Exceptions</u>, meaning that while these diphones would be generated by the above procedure, they are not in the data base. In this case, these three diphones do not occur in English, i.e., these phoneme combinations do not occur. The total number of diphones can be easily calculated by multiplying the number of possible C_1 phonemes by the number of V_1 phonemes and subtracting the Exceptions. In this case, 25*24-3=597.

The category V_3V_1 diphones contains the first example of <u>Additions</u>. Additions are diphones which fit into the general category (e.g. Vowel-Vowel), but which are not captured by the listing procedure.

In the Stop Consonant Diphones with Context category, we describe the first diphones which contain the surrounding phonetic context in their specification. At this point we also introduce a new phoneme variable X, which is defined as the set of eight stop consonant phonemes. As described in early reports, diphones in context are indicated by the following notation:

$$P_a\ P_b\ /\ C_a\ \&\ C_b$$

where P_aP_b give the two phonemes defining the diphone, the "/" means "in the context of", and the "&" indicates the location of the diphone P_aP_b with preceding context C_a and following context C_b. Each of these contexts can, in general, be up to 3 phonemes in duration and include single phonemes, or classes of phonemes grouped in square brackets.

C_1V_1 DIPHONES (597)

$C_1 \equiv$

P	T	K	B	D	G	CH	JH	F	V	TH	DH	
S	Z	SH	ZH	W	Y	R	L	M	N	HH	NX	EL

$V_1 \equiv$

IY	IH	EY	EH	AE	AA	AO	AH	OW	UH	UW	ER
AY1	OY1	AW	YU	IR	OR	AR	EYR	UR	AX	IX	AXR

Exceptions: [W YU] [Y YU] [R YU]

V_2C_2 DIPHONES (597)

$V_2 \equiv V_1$ except [AY1] is replaced by [AY2] and [OY1] is replaced by [OY2]

$C_2 \equiv$

SIP	SIT	SIK	SIB	SID	SIG	SIC	SIJ	F	V	TH	DH	
S	Z	SH	ZH	W	Y	R	L	M	N	HH	NX	EL

Exceptions: [YU W] [YU Y] [YU R]

V_3V_1 DIPHONES (242)

$V_3 \equiv$ AA AO AW AY2 IY ER EY OW OY2 UW

$V_1 \equiv$ defined above

Additions: [AY1 AY2] [OY1 OY2]

C_3C_4 DIPHONES (483)

$C_3 \equiv$

P	T	K	B	D	G	CH	JH	F	V	TH	DH
S	Z	SH	ZH	R	L	M	N	NX			

$C_4 \equiv$

SIP	SIT	SIK	SIB	SID	SIG	SIC	SIJ	F	V	TH	DH
S	Z	SH	ZH	W	Y	R	L	M	N	HH	

Stop Consonant Diphones with Context		(544)
SIX X / & V_1	V_1 ≡ defined above	(192)
SIX X / & C_4	C_4 ≡ defined above	(184)
SIX X / C_3 &	C_3 ≡ defined above	(168)
X ≡ P T K B D G CH JH		

Diphones with Silence		(81)
- V_4	V_4 ≡ V_1 less [AX] [IX] [AXR]	(21)
- C_4	C_4 ≡ defined above	(23)
V_3 -	V_3 ≡ defined above	(10)
C_5 -	C_5 ≡ C_3 less [R] [L]	(19)
SIX X / & -	X ≡ defined above	(8)

[AY] and [OY] Vowels with Context		(98)
AY1 AY2 / & V_1	V_1 defined above	(24)
AY1 AY2 / & C_2	C_2 defined above	(25)
OY1 OY2 / & V_1	V_1 defined above	(24)
OY1 OY2 / & C_2	C_2 defined above	(25)

Miscellaneous Diphones		(10)
SIK K / S & C_6	C_6 ≡ L R W	(3)
SIP P / S & C_7	C_7 ≡ L R	(2)
SIT T / S & R		(1)
- Q		(1)
Q AR		(1)
IH DX		(1)
DX EY		(1)

APPENDIX B ALPHABETIZED LIST OF DIPHONES

- AA	- AE	- AH	- AO	- AR	- AW
- AY1	- DH	- EH	- ER	- EY	- EYR
- F	- HH	- IH	- IR	- IY	- L
- M	- N	- OR	- OW	- OY1	- Q
- R	- S	- SH	- SIB	- SIC	- SID
- SIG	- SIJ	- SIK	- SIP	- SIT	- TH
- UH	- UR	- UW	- V	- W	- Y
- YU	- Z	- ZH	AA -	AA AA	AA AE
AA AH	AA AO	AA AR	AA AW	AA AX	AA AXR
AA AY1	AA DH	AA EH	AA EL	AA ER	AA EY
AA EYR	AA F	AA HH	AA IH	AA IR	AA IX
AA IY	AA L	AA M	AA N	AA NX	AA OR
AA OW	AA OY1	AA R	AA S	AA SH	AA SIB
AA SIC	AA SID	AA SIG	AA SIJ	AA SIK	AA SIP
AA SIT	AA TH	AA UH	AA UR	AA UW	AA V
AA W	AA Y	AA YU	AA Z	AA ZH	AE DH
AE EL	AE F	AE HH	AE L	AE M	AE N
AE NX	AE R	AE S	AE SH	AE SIB	AE SIC
AE SID	AE SIG	AE SIJ	AE SIK	AE SIP	AE SIT
AE TH	AE V	AE W	AE Y	AE Z	AE ZH
AH DH	AH EL	AH F	AH HH	AH L	AH M
AH N	AH NX	AH R	AH S	AH SH	AH SIB
AH SIC	AH SID	AH SIG	AH SIJ	AH SIK	AH SIP
AH SIT	AH TH	AH V	AH W	AH Y	AH Z
AH ZH	AO -	AO AA	AO AE	AO AH	AO AO
AO AR	AO AW	AO AX	AO AXR	AO AY1	AO DH
AO EH	AO EL	AO ER	AO EY	AO EYR	AO F
AO HH	AO IH	AO IR	AO IX	AO IY	AO L
AO M	AO N	AO NX	AO OR	AO OW	AO OY1
AO R	AO S	AO SH	AO SIB	AO SIC	AO SID
AO SIG	AO SIJ	AO SIK	AO SIP	AO SIT	AO TH
AO UH	AO UR	AO UW	AO V	AO W	AO Y
AO YU	AO Z	AO ZH	AR DH	AR EL	AR F
AR HH	AR L	AR M	AR N	AR NX	AR R
AR S	AR SH	AR SIB	AR SIC	AR SID	AR SIG
AR SIJ	AR SIK	AR SIP	AR SIT	AR TH	AR V
AR W	AR Y	AR Z	AR ZH	AW -	AW AA
AW AE	AW AH	AW AO	AW AR	AW AW	AW AX
AW AXR	AW AY1	AW DH	AW EH	AW EL	AW ER
AW EY	AW EYR	AW F	AW HH	AW IH	AW IR
AW IX	AW IY	AW L	AW M	AW N	AW NX
AW OR	AW OW	AW OY1	AW R	AW S	AW SH
AW SIB	AW SIC	AW SID	AW SIG	AW SIJ	AW SIK
AW SIP	AW SIT	AW TH	AW UH	AW UR	AW UW

AW V	AW W	AW Y	AW YU	AW Z	AW ZH
AX DH	AX EL	AX F	AX HH	AX L	AX M
AX N	AX NX	AX R	AX S	AX SH	AX SIB
AX SIC	AX SID	AX SIG	AX SIJ	AX SIK	AX SIP
AX SIT	AX TH	AX V	AX W	AX Y	AX Z
AX ZH	AXR DH	AXR EL	AXR F	AXR HH	AXR L
AXR M	AXR N	AXR NX	AXR R	AXR S	AXR SH
AXR SIB	AXR SIC	AXR SID	AXR SIG	AXR SIJ	AXR SIK
AXR SIP	AXR SIT	AXR TH	AXR V	AXR W	AXR Y
AXR Z	AXR ZH	AY1 AY2			
AY1 AY2 / & AA		AY1 AY2 / & AE		AY1 AY2 / & AH	
AY1 AY2 / & AO		AY1 AY2 / & AR		AY1 AY2 / & AW	
AY1 AY2 / & AX		AY1 AY2 / & AXR		AY1 AY2 / & AY1	
AY1 AY2 / & DH		AY1 AY2 / & EH		AY1 AY2 / & EL	
AY1 AY2 / & ER		AY1 AY2 / & EY		AY1 AY2 / & EYR	
AY1 AY2 / & F		AY1 AY2 / & HH		AY1 AY2 / & IH	
AY1 AY2 / & IR		AY1 AY2 / & IX		AY1 AY2 / & IY	
AY1 AY2 / & L		AY1 AY2 / & M		AY1 AY2 / & N	
AY1 AY2 / & NX		AY1 AY2 / & OR		AY1 AY2 / & OW	
AY1 AY2 / & OY1		AY1 AY2 / & R		AY1 AY2 / & S	
AY1 AY2 / & SH		AY1 AY2 / & SIB		AY1 AY2 / & SIC	
AY1 AY2 / & SID		AY1 AY2 / & SIG		AY1 AY2 / & SIJ	
AY1 AY2 / & SIK		AY1 AY2 / & SIP		AY1 AY2 / & SIT	
AY1 AY2 / & TH		AY1 AY2 / & UH		AY1 AY2 / & UR	
AY1 AY2 / & UW		AY1 AY2 / & V		AY1 AY2 / & W	
AY1 AY2 / & Y		AY1 AY2 / & YU		AY1 AY2 / & Z	
AY1 AY2 / & ZH					
AY2 -	AY2 AA	AY2 AE	AY2 AH	AY2 AO	AY2 AR
AY2 AW	AY2 AX	AY2 AXR	AY2 AY1	AY2 DH	AY2 EH
AY2 EL	AY2 ER	AY2 EY	AY2 EYR	AY2 F	AY2 HH
AY2 IH	AY2 IR	AY2 IX	AY2 IY	AY2 L	AY2 M
AY2 N	AY2 NX	AY2 OR	AY2 OW	AY2 OY1	AY2 R
AY2 S	AY2 SH	AY2 SIB	AY2 SIC	AY2 SID	AY2 SIG
AY2 SIJ	AY2 SIK	AY2 SIP	AY2 SIT	AY2 TH	AY2 UH
AY2 UR	AY2 UW	AY2 V	AY2 W	AY2 Y	AY2 YU
AY2 Z	AY2 ZH	B -	B AA	B AE	B AH
B AC	B AR	B AW	B AX	B AXR	B AY1
B DH	B EH	B ER	B EY	B EYR	B F
B HH	B IH	B IR	B IX	B IY	B L
B M	B N	B OR	B OW	B OY1	B R
B S	B SH	B SIB	B SIC	B SID	B SIG
B SIJ	B SIK	B SIP	B SIT	B TH	B UH
B UR	B UW	B V	B W	B Y	B YU
B Z	B ZH	CH -	CH AA	CH AE	CH AH
CH AO	CH AR	CH AW	CH AX	CH AXR	CH AY1
CH DH	CH EH	CH ER	CH EY	CH EYR	CH F
CH HH	CH IH	CH IR	CH IX	CH IY	CH L

CH M	CH N	CH OR	CH OW	CH OY1	CH R
CH S	CH SH	CH SIB	CH SIC	CH SID	CH SIG
CH SIJ	CH SIK	CH SIP	CH SIT	CH TH	CH UH
CH UR	CH UW	CH V	CH W	CH Y	CH YU
CH Z	CH ZH	D -	D AA	D AE	D AH
D AO	D AR	D AW	D AX	D AXR	D AY1
D DH	D EH	D ER	D EY	D EYR	D F
D HH	D IH	D IR	D IX	D IY	D L
D M	D N	D OR	D OW	D OY1	D R
D S	D SH	D SIB	D SIC	D SID	D SIG
D SIJ	D SIK	D SIP	D SIT	D TH	D UH
D UR	D UW	D V	D W	D Y	D YU
D Z	D ZH	DH -	DH AA	DH AE	DH AH
DH AO	DH AR	DH AW	DH AX	DH AXR	DH AY1
DH DH	DH EH	DH ER	DH EY	DH EYR	DH F
DH HH	DH IH	DH IR	DH IX	DH IY	DH L
DH M	DH N	DH OR	DH OW	DH OY1	DH R
DH S	DH SH	DH SIB	DH SIC	DH SID	DH SIG
DH SIJ	DH SIK	DH SIP	DH SIT	DH TH	DH UH
DH UR	DH UW	DH V	DH W	DH Y	DH YU
DH Z	DH ZH	DX EY	EH DH	EH EL	EH F
EH HH	EH L	EH M	EH N	EH NX	EH R
EH S	EH SH	EH SIB	EH SIC	EH SID	EH SIG
EH SIJ	EH SIK	EH SIP	EH SIT	EH TH	EH V
EH W	EH Y	EH Z	EH ZH	EL AA	EL AE
EL AH	EL AO	EL AR	EL AW	EL AXR	EL AY1
EL EH	EL ER	EL EY	EL EYR	EL IH	EL IR
EL IX	EL IY	EL NX	EL OR	EL OW	EL OY1
EL UH	EL UR	EL UW	EL YU	ER -	ER AA
ER AE	ER AH	ER AO	ER AR	ER AW	ER AX
ER AXR	ER AY1	ER DH	ER EH	ER EL	ER ER
ER EY	ER EYR	ER F	ER HH	ER IH	ER IR
ER IX	ER IY	ER L	ER M	ER N	ER NX
ER OR	ER OW	ER OY1	ER R	ER S	ER SH
ER SIB	ER SIC	ER SID	ER SIG	ER SIJ	ER SIK
ER SIP	ER SIT	ER TH	ER UH	ER UR	ER UW
ER V	ER W	ER Y	ER YU	ER Z	ER ZH
EY -	EY AA	EY AE	EY AH	EY AO	EY AR
EY AW	EY AX	EY AXR	EY AY1	EY DH	EY EH
EY EL	EY ER	EY EY	EY EYR	EY F	EY HH
EY IH	EY IR	EY IX	EY IY	EY L	EY M
EY N	EY NX	EY OR	EY OW	EY OY1	EY R
EY S	EY SH	EY SIB	EY SIC	EY SID	EY SIG
EY SIJ	EY SIK	EY SIP	EY SIT	EY TH	EY UH
EY UR	EY UW	EY V	EY W	EY Y	EY YU
EY Z	EY ZH	EYR DH	EYR EL	EYR F	EYR HH
EYR L	EYR M	EYR N	EYR NX	EYR R	EYR S

EYR SH	EYR SIB	EYR SIC	EYR SID	EYR SIG	EYR SIJ
EYR SIK	EYR SIP	EYR SIT	EYR TH	EYR V	EYR W
EYR Y	EYR Z	EYR ZH	F -	F AA	F AE
F AH	F AO	F AR	F AW	F AX	F AXR
F AY1	F DH	F EH	F ER	F EY	F EYR
F F	F HH	F IH	F IR	F IX	F IY
F L	F M	F N	F OR	F OW	F OY1
F R	F S	F SH	F SIB	F SIC	F SID
F SIG	F SIJ	F SIK	F SIP	F SIT	F TH
F UH	F UR	F UW	F V	F W	F Y
F YU	F Z	F ZH	G -	G AA	G AE
G AH	G AO	G AR	G AW	G AX	G AXR
G AY1	G DH	G EH	G ER	G EY	G EYR
G F	G HH	G IH	G IR	G IX	G IY
G L	G M	G N	G OR	G OW	G OY1
G R	G S	G SH	G SIB	G SIC	G SID
G SIG	G SIJ	G SIK	G SIP	G SIT	G TH
G UH	G UR	G UW	G V	G W	G Y
G YU	G Z	G ZH	HH AA	HH AE	HH AH
HH AO	HH AR	HH AW	HH AX	HH AXR	HH AY1
HH EH	HH ER	HH EY	HH EYR	HH IH	HH IR
HH IX	HH IY	HH OR	HH OW	HH OY1	HH UH
HH UR	HH UW	HH YU	IH DH	IH DX	IH EL
IH F	IH HH	IH L	IH M	IH N	IH NX
IH R	IH S	IH SH	IH SIB	IH SIC	IH SID
IH SIG	IH SIJ	IH SIK	IH SIP	IH SIT	IH TH
IH V	IH W	IH Y	IH Z	IH ZH	IR DH
IR EL	IR F	IR HH	IR L	IR M	IR N
IR NX	IR R	IR S	IR SH	IR SIB	IR SIC
IR SID	IR SIG	IR SIJ	IR SIK	IR SIP	IR SIT
IR TH	IR V	IR W	IR Y	IR Z	IR ZH
IX DH	IX EL	IX F	IX HH	IX L	IX M
IX N	IX NX	IX R	IX S	IX SH	IX SIB
IX SIC	IX SID	IX SIG	IX SIJ	IX SIK	IX SIP
IX SIT	IX TH	IX V	IX W	IX Y	IX Z
IX ZH	IY -	IY AA	IY AE	IY AH	IY AO
IY AR	IY AW	IY AX	IY AXR	IY AY1	IY DH
IY EH	IY EL	IY ER	IY EY	IY EYR	IY F
IY HH	IY IH	IY IR	IY IX	IY IY	IY L
IY M	IY N	IY NX	IY OR	IY OW	IY OY1
IY R	IY S	IY SH	IY SIB	IY SIC	IY SID
IY SIG	IY SIJ	IY SIK	IY SIP	IY SIT	IY TH
IY UH	IY UR	IY UW	IY V	IY W	IY Y
IY YU	IY Z	IY ZH	JH -	JH AA	JH AE
JH AH	JH AO	JH AR	JH AW	JH AX	JH AXR
JH AY1	JH DH	JH EH	JH ER	JH EY	JH EYR
JH F	JH HH	JH IH	JH IR	JH IX	JH IY

JH L	JH M	JH N	JH OR	JH OW	JH OY1
JH R	JH S	JH SH	JH SIB	JH SIC	JH SID
JH SIG	JH SIJ	JH SIK	JH SIP	JH SIT	JH TH
JH UH	JH UR	JH UW	JH V	JH W	JH Y
JH YU	JH Z	JH ZH	K -	K AA	K AE
K AH	K AO	K AR	K AW	K AX	K AXR
K AY1	K DH	K EH	K ER	K EY	K EYR
K F	K HH	K IH	K IR	K IX	K IY
K L	K M	K N	K OR	K OW	K OY1
K R	K S	K SH	K SIB	K SIC	K SID
K SIG	K SIJ	K SIK	K SIP	K SIT	K TH
K UH	K UR	K UW	K V	K W	K Y
K YU	K Z	K ZH	L AA	L AE	L AH
L AO	L AR	L AW	L AX	L AXR	L AY1
L DH	L EH	L ER	L EY	L EYR	L F
L HH	L IH	L IR	L IX	L IY	L L
L M	L N	L OR	L OW	L OY1	L R
L S	L SH	L SIB	L SIC	L SID	L SIG
L SIJ	L SIK	L SIP	L SIT	L TH	L UH
L UR	L UW	L V	L W	L Y	L YU
L Z	L ZH	M -	M AA	M AE	M AH
M AO	M AR	M AW	M AX	M AXR	M AY1
M DH	M EH	M ER	M EY	M EYR	M F
M HH	M IH	M IR	M IX	M IY	M L
M M	M N	M OR	M OW	M OY1	M R
M S	M SH	M SIB	M SIC	M SID	M SIG
M SIJ	M SIK	M SIP	M SIT	M TH	M UH
M UR	M UW	M V	M W	M Y	M YU
M Z	M ZH	N -	N AA	N AE	N AH
N AO	N AR	N AW	N AX	N AXR	N AY1
N DH	N EH	N ER	N EY	N EYR	N F
N HH	N IH	N IR	N IX	N IY	N L
N M	N N	N OR	N OW	N OY1	N R
N S	N SH	N SIB	N SIC	N SID	N SIG
N SIJ	N SIK	N SIP	N SIT	N TH	N UH
N UR	N UW	N V	N W	N Y	N YU
N Z	N ZH	NX -	NX AA	NX AE	NX AH
NX AO	NX AR	NX AW	NX AX	NX AXR	NX AY1
NX DH	NX EH	NX ER	NX EY	NX EYR	NX F
NX HH	NX IH	NX IR	NX IX	NX IY	NX L
NX M	NX N	NX OR	NX OW	NX OY1	NX R
NX S	NX SH	NX SIB	NX SIC	NX SID	NX SIG
NX SIJ	NX SIK	NX SIP	NX SIT	NX TH	NX UH
NX UR	NX UW	NX V	NX W	NX Y	NX YU
NX Z	NX ZH	OR DH	OR EL	OR F	OR HH
OR L	OR M	OR N	OR NX	OR R	OR S
OR SH	OR SIB	OR SIC	OR SID	OR SIG	OR SIJ

OR SIK	OR SIP	OR SIT	OR TH	OR V	OR W
OR Y	OR Z	OR ZH	OW -	OW AA	OW AE
OW AH	OW AO	OW AR	OW AW	OW AX	OW AXR
OW AY1	OW DH	OW EH	OW EL	OW ER	OW EY
OW EYR	OW F	OW HH	OW IH	OW IR	OW IX
OW IY	OW L	OW M	OW N	OW NX	OW OR
OW OW	OW OY1	OW R	OW S	OW SH	OW SIB
OW SIC	OW SID	OW SIG	OW SIJ	OW SIK	OW SIP
OW SIT	OW TH	OW UH	OW UR	OW UW	OW V
OW W	OW Y	OW YU	OW Z	OW ZH	OY IY
OY1 OY2					
OY1 OY2 / & AA		OY1 OY2 / & AE		OY1 OY2 / & AH	
OY1 OY2 / & AO		OY1 OY2 / & AR		OY1 OY2 / & AW	
OY1 OY2 / & AX		OY1 OY2 / & AXR		OY1 OY2 / & AY1	
OY1 OY2 / & DH		OY1 OY2 / & EH		OY1 OY2 / & EL	
OY1 OY2 / & ER		OY1 OY2 / & EY		OY1 OY2 / & EYR	
OY1 OY2 / & F		OY1 OY2 / & HH		OY1 OY2 / & IH	
OY1 OY2 / & IR		OY1 OY2 / & IX		OY1 OY2 / & IY	
OY1 OY2 / & L		OY1 OY2 / & M		OY1 OY2 / & N	
OY1 OY2 / & NX		OY1 OY2 / & OR		OY1 OY2 / & OW	
OY1 OY2 / & OY1		OY1 OY2 / & R		OY1 OY2 / & S	
OY1 OY2 / & SH		OY1 OY2 / & SIB		OY1 OY2 / & SIC	
OY1 OY2 / & SID		OY1 OY2 / & SIG		OY1 OY2 / & SIJ	
OY1 OY2 / & SIK		OY1 OY2 / & SIP		OY1 OY2 / & SIT	
OY1 OY2 / & TH		OY1 OY2 / & UH		OY1 OY2 / & UR	
OY1 OY2 / & UW		OY1 OY2 / & V		OY1 OY2 / & W	
OY1 OY2 / & Y		OY1 OY2 / & YU		OY1 OY2 / & Z	
OY1 OY2 / & ZH					
OY2 -	OY2 AA	OY2 AE	OY2 AH	OY2 AO	OY2 AR
OY2 AW	OY2 AX	OY2 AXR	OY2 AY1	OY2 DH	OY2 EH
OY2 EL	OY2 ER	OY2 EY	OY2 EYR	OY2 F	OY2 HH
OY2 IH	OY2 IR	OY2 IX	OY2 L	OY2 M	OY2 N
OY2 NX	OY2 OR	OY2 OW	OY2 OY1	OY2 R	OY2 S
OY2 SH	OY2 SIB	OY2 SIC	OY2 SID	OY2 SIG	OY2 SIJ
OY2 SIK	OY2 SIP	OY2 SIT	OY2 TH	OY2 UH	OY2 UR
OY2 UW	OY2 V	OY2 W	OY2 Y	OY2 YU	OY2 Z
OY2 ZH	P -	P AA	P AE	P AH	P AO
P AR	P AW	P AX	P AXR	P AY1	P DH
P EH	P ER	P EY	P EYR	P F	P HH
P IH	P IR	P IX	P IY	P L	P M
P N	P OR	P OW	P OY1	P R	P S
P SH	P SIB	P SIC	P SID	P SIG	P SIJ
P SIK	P SIP	P SIT	P TH	P UH	P UR
P UW	P V	P W	P Y	P YU	P Z
P ZH	Q AR	R AA	R AE	R AH	R AO
R AR	R AW	R AX	R AXR	R AY1	R DH
R EH	R ER	R EY	R EYR	R F	R HH

R IH	R IR	R IX	R IY	R L	R M
R N	R OR	R OW	R OY1	R R	R S
R SH	R SIB	R SIC	R SID	R SIG	R SIJ
R SIK	R SIP	R SIT	R TH	R UH	R UR
R UW	R V	R W	R Y	R Z	R ZH
S -	S AA	S AE	S AH	S AO	S AR
S AW	S AX	S AXR	S AY1	S DH	S EH
S ER	S EY	S EYR	S F	S HH	S IH
S IR	S IX	S IY	S L	S M	S N
S OR	S OW	S OY1	S R	S S	S SH
S SIB	S SIC	S SID	S SIG	S SIJ	S SIK
S SIP	S SIT	S TH	S UH	S UR	S UW
S V	S W	S Y	S YU	S Z	S ZH
SH -	SH AA	SH AE	SH AH	SH AO	SH AR
SH AW	SH AX	SH AXR	SH AY1	SH DH	SH EH
SH ER	SH EY	SH EYR	SH F	SH HH	SH IH
SH IR	SH IX	SH IY	SH L	SH M	SH N
SH OR	SH OW	SH OY1	SH R	SH S	SH SH
SH SIB	SH SIC	SH SID	SH SIG	SH SIJ	SH SIK
SH SIP	SH SIT	SH TH	SH UH	SH UR	SH UW
SH V	SH W	SH Y	SH YU	SH Z	SH ZH

SIB B / & -	SIB B / & AA	SIB B / & AE
SIB B / & AH	SIB B / & AO	SIB B / & AR
SIB B / & AW	SIB B / & AX	SIB B / & AXR
SIB B / & AY1	SIB B / & DH	SIB B / & EH
SIB B / & ER	SIB B / & EY	SIB B / & EYR
SIB B / & F	SIB B / & HH	SIB B / & IH
SIB B / & IR	SIB B / & IX	SIB B / & IY
SIB B / & L	SIB B / & M	SIB B / & N
SIB B / & OR	SIB B / & OW	SIB B / & OY1
SIB B / & R	SIB B / & S	SIB B / & SH
SIB B / & SIB	SIB B / & SIC	SIB B / & SID
SIB B / & SIG	SIB B / & SIJ	SIB B / & SIK
SIB B / & SIP	SIB B / & SIT	SIB B / & TH
SIB B / & UH	SIB B / & UR	SIB B / & UW
SIB B / & V	SIB B / & W	SIB B / & Y
SIB B / & YU	SIB B / & Z	SIB B / & ZH
SIB B / B &	SIB B / CH &	SIB B / D &
SIB B / DH &	SIB B / F &	SIB B / G &
SIB B / JH &	SIB B / K &	SIB B / L &
SIB B / M &	SIB B / N &	SIB B / NX &
SIB B / P &	SIB B / R &	SIB B / S &
SIB B / SH &	SIB B / T &	SIB B / TH &
SIB B / V &	SIB B / Z &	SIB B / ZH &
SIC CH / & -	SIC CH / & AA	SIC CH / & AE
SIC CH / & AH	SIC CH / & AO	SIC CH / & AR
SIC CH / & AW	SIC CH / & AX	SIC CH / & AXR

SIC CH / & AY1	SIC CH / & DH	SIC CH / & EH
SIC CH / & ER	SIC CH / & EY	SIC CH / & EYR
SIC CH / & F	SIC CH / & HH	SIC CH / & IH
SIC CH / & IR	SIC CH / & IX	SIC CH / & IY
SIC CH / & L	SIC CH / & M	SIC CH / & N
SIC CH / & OR	SIC CH / & OW	SIC CH / & OY1
SIC CH / & R	SIC CH / & S	SIC CH / & SH
SIC CH / & SIB	SIC CH / & SIC	SIC CH / & SID
SIC CH / & SIG	SIC CH / & SIJ	SIC CH / & SIK
SIC CH / & SIP	SIC CH / & SIT	SIC CH / & TH
SIC CH / & UH	SIC CH / & UR	SIC CH / & UW
SIC CH / & V	SIC CH / & W	SIC CH / & Y
SIC CH / & YU	SIC CH / & Z	SIC CH / & ZH
SIC CH / B &	SIC CH / CH &	SIC CH / D &
SIC CH / DH &	SIC CH / F &	SIC CH / G &
SIC CH / M &	SIC CH / N &	SIC CH / NX &
SIC CH / P &	SIC CH / R &	SIC CH / S &
SIC CH / SH &	SIC CH / T &	SIC CH / TH &
SIC CH / V &	SIC CH / Z &	SIC CH / ZH &
SID D / & -	SID D / & AA	SID D / & AE
SID D / & AH	SID D / & AO	SID D / & AR
SID D / & AW	SID D / & AX	SID D / & AXR
SID D / & AY1	SID D / & DH	SID D / & EH
SID D / & ER	SID D / & EY	SID D / & EYR
SID D / & F	SID D / & HH	SID D / & IH
SID D / & IR	SID D / & IX	SID D / & IY
SID D / & L	SID D / & M	SID D / & N
SID D / & OR	SID D / & OW	SID D / & OY1
SID D / & R	SID D / & S	SID D / & SH
SID D / & SIB	SID D / & SIC	SID D / & SID
SID D / & SIG	SID D / & SIJ	SID D / & SIK
SID D / & SIP	SID D / & SIT	SID D / & TH
SID D / & UH	SID D / & UR	SID D / & UW
SID D / & V	SID D / & W	SID D / & Y
SID D / & YU	SID D / & Z	SID D / & ZH
SID D / B &	SID D / CH &	SID D / D &
SID D / DH &	SID D / F &	SID D / G &
SID D / JH &	SID D / K &	SID D / L &
SID D / M &	SID D / N &	SID D / NX &
SID D / P &	SID D / R &	SID D / S &
SID D / SH &	SID D / T &	SID D / TH &
SID D / V &	SID D / Z &	SID D / ZH &
SIG G / & -	SIG G / & AA	SIG G / & AE
SIG G / & AH	SIG G / & AO	SIG G / & AR
SIG G / & AW	SIG G / & AX	SIG G / & AXR
SIG G / & AY1	SIG G / & DH	SIG G / & EH
SIG G / & ER	SIG G / & EY	SIG G / & EYR

SIG G / & F
SIG G / & IR
SIG G / & L
SIG G / & OR
SIG G / & R
SIG G / & SIB
SIG G / & SIG
SIG G / & SIP
SIG G / & UH
SIG G / & V
SIG G / & YU
SIG G / B &
SIG G / DH &
SIG G / JH &
SIG G / M &
SIG G / P &
SIG G / SH &
SIG G / V &
SIJ JH / & -
SIJ JH / & AH
SIJ JH / & AW
SIJ JH / & AY1
SIJ JH / & ER
SIJ JH / & F
SIJ JH / & IR
SIJ JH / & L
SIJ JH / & OR
SIJ JH / & R
SIJ JH / & SIB
SIJ JH / & SIG
SIJ JH / & SIP
SIJ JH / & UH
SIJ JH / & V
SIJ JH / & YU
SIJ JH / B &
SIJ JH / DH &
SIJ JH / JH &
SIJ JH / M &
SIJ JH / P &
SIJ JH / SH &
SIJ JH / V &
SIK K / & -
SIK K / & AH
SIK K / & AW
SIK K / & AY1
SIK K / & ER
SIK K / & F

SIG G / & HH
SIG G / & IX
SIG G / & M
SIG G / & OW
SIG G / & S
SIG G / & SIC
SIG G / & SIJ
SIG G / & SIT
SIG G / & UR
SIG G / & W
SIG G / & Z
SIG G / CH &
SIG G / F &
SIG G / K &
SIG G / N &
SIG G / R &
SIG G / T &
SIG G / Z &
SIJ JH / & AA
SIJ JH / & AO
SIJ JH / & AX
SIJ JH / & DH
SIJ JH / & EY
SIJ JH / & HH
SIJ JH / & IX
SIJ JH / & M
SIJ JH / & OW
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SIJ JH / & SIC
SIJ JH / & SIJ
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SIJ JH / & UR
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SIJ JH / CH &
SIJ JH / F &
SIJ JH / K &
SIJ JH / N &
SIJ JH / R &
SIJ JH / T &
SIJ JH / Z &
SIK K / & AA
SIK K / & AO
SIK K / & AX
SIK K / & DH
SIK K / & EY
SIK K / & HH

SIG G / & IH
SIG G / & IY
SIG G / & N
SIG G / & OY1
SIG G / & SH
SIG G / & SID
SIG G / & SIK
SIG G / & TH
SIG G / & UW
SIG G / & Y
SIG G / & ZH
SIG G / D &
SIG G / G &
SIG G / L &
SIG G / NX &
SIG G / S &
SIG G / TH &
SIG G / ZH &
SIJ JH / & AE
SIJ JH / & AR
SIJ JH / & AXR
SIJ JH / & EH
SIJ JH / & EYR
SIJ JH / & IH
SIJ JH / & IY
SIJ JH / & N
SIJ JH / & OY1
SIJ JH / & SH
SIJ JH / & SID
SIJ JH / & SIK
SIJ JH / & TH
SIJ JH / & UW
SIJ JH / & Y
SIJ JH / & ZH
SIJ JH / D &
SIJ JH / G &
SIJ JH / L &
SIJ JH / NX &
SIJ JH / S &
SIJ JH / TH &
SIJ JH / ZH &
SIK K / & AE
SIK K / & AR
SIK K / & AXR
SIK K / & EH
SIK K / & EYR
SIK K / & IH

SIK K / & IR	SIK K / & IX	SIK K / & IY
SIK K / & L	SIK K / & M	SIK K / & N
SIK K / & OR	SIK K / & OW	SIK K / & OY1
SIK K / & R	SIK K / & S	SIK K / & SH
SIK K / & SIB	SIK K / & SIC	SIK K / & SID
SIK K / & SIG	SIK K / & SIJ	SIK K / & SIK
SIK K / & SIP	SIK K / & SIT	SIK K / & TH
SIK K / & UH	SIK K / & UR	SIK K / & UW
SIK K / & V	SIK K / & W	SIK K / & Y
SIK K / & YU	SIK K / & Z	SIK K / & ZH
SIK K / B &	SIK K / CH &	SIK K / D &
SIK K / DH &	SIK K / F &	SIK K / G &
SIK K / JH &	SIK K / K &	SIK K / L &
SIK K / M &	SIK K / N &	SIK K / NX &
SIK K / P &	SIK K / R &	SIK K / S &
SIK K / S & L	SIK K / S & R	SIK K / S & W
SIK K / SH &	SIK K / T &	SIK K / TH &
SIK K / V &	SIK K / Z &	SIK K / ZH &
SIP P / & -	SIP P / & AA	SIP P / & AE
SIP P / & AH	SIP P / & AO	SIP P / & AR
SIP P / & AW	SIP P / & AX	SIP P / & AXR
SIP P / & AY1	SIP P / & DH	SIP P / & EH
SIP P / & ER	SIP P / & EY	SIP P / & EYR
SIP P / & F	SIP P / & HH	SIP P / & IH
SIP P / & IR	SIP P / & IX	SIP P / & IY
SIP P / & L	SIP P / & M	SIP P / & N
SIP P / & OR	SIP P / & OW	SIP P / & OY1
SIP P / & R	SIP P / & S	SIP P / & SH
SIP P / & SIB	SIP P / & SIC	SIP P / & SID
SIP P / & SIG	SIP P / & SIJ	SIP P / & SIK
SIP P / & SIP	SIP P / & SIT	SIP P / & TH
SIP P / & UH	SIP P / & UR	SIP P / & UW
SIP P / & V	SIP P / & W	SIP P / & Y
SIP P / & YU	SIP P / & Z	SIP P / & ZH
SIP P / B &	SIP P / CH &	SIP P / D &
SIP P / DH &	SIP P / F &	SIP P / G &
SIP P / JH &	SIP P / K &	SIP P / L &
SIP P / M &	SIP P / N &	SIP P / NX &
SIP P / P &	SIP P / R &	SIP P / S &
SIP P / S & L	SIP P / S & R	SIP P / SH &
SIP P / T &	SIP P / TH &	SIP P / V &
SIP P / Z &	SIP P / ZH &	SIT T / & -
SIT T / & AA	SIT T / & AE	SIT T / & AH
SIT T / & AO	SIT T / & AR	SIT T / & AW
SIT T / & AX	SIT T / & AXR	SIT T / & AY1
SIT T / & DH	SIT T / & EH	SIT T / & ER
SIT T / & EY	SIT T / & EYR	SIT T / & F

SIT T / & HH	SIT T / & IH	SIT T / & IR
SIT T / & IX	SIT T / & IY	SIT T / & L
SIT T / & M	SIT T / & N	SIT T / & OR
SIT T / & OW	SIT T / & OY1	SIT T / & R
SIT T / & S	SIT T / & SH	SIT T / & SIB
SIT T / & SIC	SIT T / & SID	SIT T / & SIG
SIT T / & SIJ	SIT T / & SIK	SIT T / & SIP
SIT T / & SIT	SIT T / & TH	SIT T / & UH
SIT T / & UR	SIT T / & UW	SIT T / & V
SIT T / & W	SIT T / & Y	SIT T / & YU
SIT T / & Z	SIT T / & ZH	SIT T / B &
SIT T / CH &	SIT T / D &	SIT T / DH &
SIT T / F &	SIT T / G &	SIT T / JH &
SIT T / K &	SIT T / L &	SIT T / M &
SIT T / N &	SIT T / NX &	SIT T / P &
SIT T / R &	SIT T / S &	SIT T / S & R
SIT T / SH &	SIT T / T &	SIT T / TH &
SIT T / V &	SIT T / Z &	SIT T / ZH &

T -	T AA	T AE	T AH	T AO	T AR
T AW	T AX	T AXR	T AY1	T DH	T EH
T ER	T EY	T EYR	T F	T HH	T IH
T IR	T IX	T IY	T L	T M	T N
T OR	T OW	T OY1	T R	T S	T SH
T SIB	T SIC	T SID	T SIG	T SIJ	T SIK
T SIP	T SIT	T TH	T UH	T UR	T UW
T V	T W	T Y	T YU	T Z	T ZH
TH -	TH AA	TH AE	TH AH	TH AO	TH AR
TH AW	TH AX	TH AXR	TH AY1	TH DH	TH EH
TH ER	TH EY	TH EYR	TH F	TH HH	TH IH
TH IR	TH IX	TH IY	TH L	TH M	TH N
TH OR	TH OW	TH OY1	TH R	TH S	TH SH
TH SIB	TH SIC	TH SID	TH SIG	TH SIJ	TH SIK
TH SIP	TH SIT	TH TH	TH UH	TH UR	TH UW
TH V	TH W	TH Y	TH YU	TH Z	TH ZH
UH DH	UH EL	UH F	UH HH	UH L	UH M
UH N	UH NX	UH R	UH S	UH SH	UH SIB
UH SIC	UH SID	UH SIG	UH SIJ	UH SIK	UH SIP
UH SIT	UH TH	UH V	UH W	UH Y	UH Z
UH ZH	UR DH	UR EL	UR F	UR HH	UR L
UR M	UR N	UR NX	UR R	UR S	UR SH
UR SIB	UR SIC	UR SID	UR SIG	UR SIJ	UR SIK
UR SIP	UR SIT	UR TH	UR V	UR W	UR Y
UR Z	UR ZH	UW -	UW AA	UW AE	UW AH
UW AO	UW AR	UW AW	UW AX	UW AXR	UW AY1
UW DH	UW EH	UW EL	UW ER	UW EY	UW EYR
UW F	UW HH	UW IH	UW IR	UW IX	UW IY
UW L	UW M	UW N	UW NX	UW OR	UW OW

UW OY1	UW R	UW S	UW SH	UW SIB	UW SIC
UW SID	UW SIG	UW SIJ	UW SIK	UW SIP	UW SIT
UW TH	UW UH	UW UR	UW UW	UW V	UW W
UW Y	UW YU	UW Z	UW ZH	V -	V AA
V AE	V AH	V AO	V AR	V AW	V AX
V AXR	V AY1	V DH	V EH	V ER	V EY
V EYR	V F	V HH	V IH	V IR	V IX
V IY	V L	V M	V N	V OR	V OW
V OY1	V R	V S	V SH	V SIB	V SIC
V SID	V SIG	V SIJ	V SIK	V SIP	V SIT
V TH	V UH	V UR	V UW	V V	V W
V Y	V YU	V Z	V ZH	W AA	W AE
W AH	W AO	W AR	W AW	W AX	W AXR
W AY1	W EH	W ER	W EY	W EYR	W IH
W IR	W IX	W IY	W OR	W OW	W OY1
W UH	W UR	W UW	Y AA	Y AE	Y AH
Y AO	Y AR	Y AW	Y AX	Y AXR	Y AY1
Y EH	Y ER	Y EY	Y EYR	Y IH	Y IR
Y IX	Y IY	Y OR	Y OW	Y OY1	Y UH
Y UR	Y UW	YU DH	YU EL	YU F	YU HH
YU L	YU M	YU N	YU NX	YU S	YU SH
YU SIB	YU SIC	YU SID	YU SIG	YU SIJ	YU SIK
YU SIP	YU SIT	YU TH	YU V	YU Z	YU ZH
Z -	Z AA	Z AE	Z AH	Z AO	Z AR
Z AW	Z AX	Z AXR	Z AY1	Z DH	Z EH
Z ER	Z EY	Z EYR	Z F	Z HH	Z IH
Z IR	Z IX	Z IY	Z L	Z M	Z N
Z OR	Z OW	Z OY1	Z R	Z S	Z SH
Z SIB	Z SIC	Z SID	Z SIG	Z SIJ	Z SIK
Z SIP	Z SIT	Z TH	Z UH	Z UR	Z UW
Z V	Z W	Z Y	Z YU	Z Z	Z ZH
ZH -	ZH AA	ZH AE	ZH AH	ZH AO	ZH AR
ZH AW	ZH AX	ZH AXR	ZH AY1	ZH DH	ZH EH
ZH ER	ZH EY	ZH EYR	ZH F	ZH HH	ZH IH
ZH IR	ZH IX	ZH IY	ZH L	ZH M	ZH N
ZH OR	ZH OW	ZH OY1	ZH R	ZH S	ZH SH
ZH SIB	ZH SIC	ZH SID	ZH SIG	ZH SIJ	ZH SIK
ZH SIP	ZH SIT	ZH TH	ZH UH	ZH UR	ZH UW
ZH V	ZH W	ZH Y	ZH YU	ZH Z	ZH ZH